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RESEARCH ARTICLE

Plant spatial configurations and their influences on phenological traits of cereal and legume crops under maize-based intercropping systems

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Abstract

Introduction: Intercropping systems have a great potential for crop diversification thus increasing smallholder systems' resilience to climate change while improving soil health. However, optimal benefits associated with intercropping systems are rarely realised because of the interspecific competition for growth resources among the intercropped species.

Methodology: Six trials were established in the high and low rainfall agroecological zones of Babati district in Tanzania to assess how promising cropping systems with different plant spatial configurations would influence the phenological development of intercropped maize, bean and pigeonpea. Cropping systems under study included a sole maize system rotated with a pigeonpea-bean intercrop dubbed Doubled-up legume (DUL), maize-pigeonpea system both with and without de-topping, an innovation comprising double maize rows alternated with pigeonpea and beans (Mbili-Mbili), maize-pigeonpea system with two maize seeds sown within a 50 cm intra-row space, a vertical-architecture Meru H513-pigeonpea system and a farmer practice.

Results: Branch formation was significantly higher in DUL than in maize-based systems ($p \leq 0.05$). Seasonal weather had upto 30% influence on pigeonpea flowering, with DUL having highest ($p \leq 0.05$) flower production. The rate of pigeonpea branch and flower production in Mbili-Mbili was stable across seasons relative to other maize-pigeonpea systems. Doubled-up legume and farmer practice had pigeonpea litter yield of between 1 and $2\,\text{t ha}^{-1}$ which was at least $0.5\,\text{t ha}^{-1}$ higher than in maize-based systems ($p \leq 0.05$). During the period preceding early maize reproductive stages, Mbili-Mbili increased light interception by 30% and 63% compared to maize-based systems and DUL, respectively. Maize toppings had higher (94%) P content than stover biomass that remained until harvest.

Conclusion: Overall, maize-legume systems had higher intercropping efficacy than sole maize system, both in interception use efficiency, soil mulch cover, among other soil health benefits. Mbili-Mbili and DUL also had increased phenological benefits on intercropped legumes however, the latter was prone to seasonal weather variability.

KEYWORDS

cropping systems, doubled-up legume, intercropping, Mbili-Mbili, soil health

1 | INTRODUCTION

Revitalising agricultural production by promoting the adoption and resilience of cereal—legume intercropping is a critical pillar towards the improvement of soil fertility and food security in smallholder farmer households in sub-Saharan Africa (SSA). With changing climate, crop diversification is vital. A diversification strategy that integrates legumes in cereal-based systems could help to increase efficiency of land utilisation, save labour cost while reducing yield losses under variable seasons (Caviglia et al., 2011). Intercropping and rotation can also help to reduce expenses on external nutrient sources by improving yields of subsequent cereal crops through biological fixation of N (Chikowo et al., 2020; Kermah et al., 2018). However, the yield optimisation and soil health benefits of intercropping systems is rarely achieved following the interspecific competition for growth resources among the intercropped components (Kimaro et al., 2009; Li et al., 2011). In smallholder systems and within research studies (Kihara et al., 2020; O'Leary & Smith, 2004), fertiliser inputs are mainly targeted to the cereal crop, bolstering its growth while overlooking that of the intercropped legumes. This effect is more pronounced in maize-based systems, such as those of Tanzania, where pigeonpea (*Cajanus cajan* Millsp.) and beans (*Phaseolus vulgaris*) are integrated as the main legumes (Mugi-Ngenga et al., 2021). Both the fast-growing beans and slow-growing pigeonpea are masked by maize (*Zea mays*) resulting in up to 22% and 33% decrease in yield, respectively (Laizer et al., 2019; Venance et al., 2016). Conversely, maize yield losses of between 12% and 22% have also been reported following competition for moisture and nutrient with intercropped legumes (Mashingaidze, 2004).

Reducing the phenological effect of the intercropped components requires exploration to unlock the productivity of intercropping systems. This can be achieved through promotion of intercropping innovations that can increase the productivity of legumes without compromising yields of the maize main crop (O'Leary & Smith, 2004). One such innovation is MBILI (managing beneficial interactions for legume intercrops), developed in Kenya, with spatial configuration allowing for increased light penetration to the understorey legumes (Mucheru-Muna et al., 2010). Under MBILI strip cropping, double rows of maize are alternated with two rows of legumes, but the space between two pairs of maize rows is increased to 100 cm to enhance solar radiation reaching the legume (Woomer et al., 2004). In China, a modification of MBILI having four rows of maize alternated with six rows of soybean resulted in increased legume yield, gross revenue (3400 US$ ha^{-1}), land equivalent ratio of 1:30, increased N (258 kg ha^{-1}) accumulation, and higher residual effect on subsequent wheat crop (Zhang et al., 2015). In Malawi, a legume-based innovation dubbed doubled-up legume (DUL) was developed to exploit the benefits accrued from the complementary growth habits of the intercrops and their unique architectural design. Two grain legumes, that is, pigeonpea and groundnuts (*Arachis hypogaea* L.) were intercropped to double the benefits of increased legume productivity and soil fertility through N fixation (Chikowo et al., 2020). The system also has land equivalent ratio of up to 1.29 over the sole pigeonpea and groundnut systems (Mwila et al., 2021).

Adaptations to management practices such as varying maize densities (Prasad & Brook, 2005) have also been used to increase light penetration to the intercropped legumes. These include increasing the intra-row spacing from 25 cm to 50 cm and sowing two maize seeds per hill instead of one (Mugi-Ngenga et al., 2022b). Mashingaidze and Katsaruware (2010) documented increasing light penetration through nipping of the upper part of maize plant, 10 cm above the ear leaf, commonly known as detopping. Stripping of four to five lower maize leaves also increased photosynthetically active radiation (PAR) reaching intercropped cowpea (Katsaruware & Manyanhaire, 2009). Moreover, studies (Katsaruware & Manyanhaire, 2009; O'Leary & Smith, 2004) established the potential of plants with erectophiled leaf architectural patterns to improve light access by the legume intercrop.

While cereal-legume intercropping is prominent across SSA (Rusinamhodzi et al., 2012) there exists a huge knowledge gap on how different cereal management innovations can be exploited to optimise legume yields (Kinyua et al., 2023). For example, farmers in Tanzania can increase yields of intercropped legumes by utilising maize with vertical leaf architecture, following the release of Meru H513 variety in their market. However, intercropping benefits associated with utilising Meru H513 variety or those accrued from simple management procedures like detopping under their local intercropping systems are not documented. To bridge this important knowledge gap, a study was conducted to evaluate how plant spatial configurations of promising intercropping innovations affects the phenological traits of maize, pigeonpea and beans grown under intercropping and rotation phases in Babati, Tanzania.

2 | METHODOLOGY

2.1 | Description of the study area

The study was conducted during the 2019 and 2021 cropping seasons in high (Sabilo and Riroda villages) and low (Gallapo village) rainfall agro-ecological zones of Babati district in Tanzania. The study area, located within latitudes −4.264°S and longitude 35.48°E and dominated by Ferralsols, is characterised by smallholder mixed farming systems. The average farm holding is about 2.4 ha per household (Minot, 2010) with a complex integration of livestock and food crops. Maize is the staple crop cultivated for both commercial and subsistence use. Pigeonpea and beans are the dominant legumes intercropped with maize while chickpea and lablab are cultivated as off-season crops, to utilise the residual moisture. Except beans which are mainly cultivated for subsistence consumption, and surplus sold in local markets, all other legumes are produced for export.

2.2 | Experimental design

For each of the three villages, two researcher-designed and managed trials were established, and randomisation done for each

TABLE 1 Structure of treatments implemented during the 2019–2021 seasons in Babati, Tanzania.

No. of treatment	Description
1	Sole maize: Maize planted at a spacing of 25 × 90 cm. *Maize was cultivated as a sole crop in first season and rotated with DUL*
2	Maize—Pigeonpea: Maize was planted at 25 × 90 cm and intercropped with pigeonpea (50 cm between maize rows). Maize *crop was not de-topped at physiological maturity*
3	Maize—Pigeonpea: maize was planted at 25 × 90 cm and intercropped with pigeonpea (50 cm between maize rows). *Maize was de-topped (nipped 10 cm from ear leaf) at physiological maturity*
4	Doubled-up legume: DUL had pigeonpea at 50 × 90 cm and two rows of beans in the pigeonpea intra-rows. *A season of DUL was rotated with a sole maize system in the consecutive season*
5	Maize 2 plants per hill: maize was planted at 50 × 90 cm and intercropped with pigeonpea (50 cm between maize rows). *Maize was de-topped at physiological maturity*
6	Mbili-Mbili: Two rows of maize planted at 25 × 50 cm) was intercropped with two rows of pigeonpea and a row of beans sneaked the pigeonpea rows. *Four bottom leaves of maize* were *stripped at between silking and milk stage*
7	Meru 513: Maize was planted at 25 × 90 cm and intercropped with pigeonpea (50 cm between maize rows). *Meru 513 has a vertical leaf architecture*
8	Farmer practice[a]: *Maize was* intercropped with pigeonpea. *Seeds were broadcasted behind tractor plough and the system was farmer managed. Maize crop did not receive any nutrient amendments.*

[a] The treatment was assessed only during the 2020 and 2021 seasons.

independent trial. The layout was in a randomised complete block design with three replicates and seven treatments laid on plots measuring 5 × 7 m. Maize was spaced at 90 × 25 cm and pigeonpea at an intra-row spacing of 50 cm between maize rows. Treatments comprised: (1) a sole maize system rotated with (2) a pigeonpea-bean intercrop called doubled-up legume, (3) maize-pigeonpea system both with and without de-topping, (4) an innovation comprising double maize rows alternated with pigeonpea and beans (Mbili-Mbili), (5) maize-pigeonpea system with two maize seeds sown within a 50 cm intra-row space, (6) a vertical-architecture maize called Meru H513-pigeonpea system and (7) a farmer practice (Table 1). For Mbili-Mbili, the design for MBILI system (Woomer et al., 2004) was integrated with that of doubled-up legume (Chikowo et al., 2020) to form an innovation that would accommodate two species of legumes instead of one, and not affect yields of the maize maincrop (Kinyua et al., 2023). In Mbili-Mbili system, two rows of maize (50 × 25 cm) were alternated with two rows of pigeonpea and a row of beans. In doubled-up legumes, beans were spaced at 45 × 15 cm and intercropped with pigeonpea at 90 × 50 cm.

2.3 | Field management practices

All fields were ploughed and harrowed using tractor-drawn ploughs before the onset of the rains. Except for the treatment where Meru H513 was planted throughout the season, Syngenta H524 was planted in 2020 and Dekalb 8031 in 2021 as guided by seasonal weather forecasts. The bean variety planted in both DUL and Mbili-Mbili was Jesica while pigeonpea was the long duration *ICEAP 00040* variety. During planting, P in form of Minjingu Nafaka Plus, comprising of P (16% P_2O_5) and blended with N (9%), K (6%), CaO (25%), S (5%), MgO (2%), Zn (0.5%), and B (0.1%), was basal applied on maize at a rate of 20 kg P ha^{-1} as recommended by Kihara et al. (2020). At V6 (i.e., six fully developed leaves) stage of maize development, Minjingu Topdresing fertiliser comprising of N (27%), P_2O_5 (10%), and CaO (15%) was also applied. Weeding was done both at V6 and V12 (i.e., 12 fully developed leaves) stages. A second bean phase was planted after harvesting the first bean crop in both Mbili-Mbili and doubled-up legume technologies to take advantage of the available soil moisture and space before pigeonpea could form a canopy.

2.4 | Weather characteristics during study

Weather data was collected using automatic weather stations (WatchDog 2000 Series by Spectrum Technologies Inc.) installed in Gallapo and Sabilo sites. The rainfall pattern in Sabilo resembled that of Riroda due to the proximity of the two sites.

2.5 | Soil characteristics

2.5.1 | Initial soil nutrient characterisation

Soils were sampled at 0–20 cm depth in each of the three replicates during the establishment of each trial. In addition, undisturbed natural vegetation was identified, and soil samples collected for nutrient comparison with the farmer fields. A similar sampling depth was used during sample collection in the natural vegetation. Soil pH was determined in water using a soil: water ratio of 1:2.5 while total N and C was assessed using Duma's combustion in CN elementar analyser (Vagen et al., 2010). For available P, S, Cu, Zn, B, and Fe, samples were extracted using Mehlich-3 extraction method (Mehlich, 1984) at the Crop Nutrition Laboratory (Cropnuts) in Nairobi.

2.5.2 | Soil moisture and temperature assessment

Soil moisture and temperature were assessed between the V6 stage and pigeonpea maturity using TEROS 12 sensor and the Em50 ProCheck device (Decagon Devices Inc.). Measurements were done at five randomly selected points within each net plot.

2.6 | Pigeonpea and maize phenological traits

2.6.1 | Pigeonpea branch production

The number of pigeonpea branches produced by pigeonpea plants were assessed 2 and 4 weeks before the harvesting of maize in the 2020 and 2021 seasons. A net plot of 16 m^2 was marked and the number of branches in pigeonpea plants counted and averaged.

2.6.2 | Pigeonpea flower development

For the 2020 and 2021 seasons, the number of pigeonpea plants that had flowered was assessed in the period between 2 weeks before and 2 weeks after maize was harvested in 2020, and 2 weeks, before and after, in the 2021 season. The rate of flowering was determined by counting the number of pigeonpea plants that had produced flowers during the assessment period.

2.6.3 | Pigeonpea litter fall

The quantity of abscised pigeon pea leaves was assessed by electing six wooden pegs within the net plots after which mesh traps measuring 90 × 1 m were fitted 5 cm above the ground. To avoid scattering by winds, the litter sample was assessed fortnightly by collecting all the abscised leaves trapped on the mesh. The collected leaf litter was put in well-labelled sample bags and transported to the laboratory for weight determination and ovendried at 60°C. For quality assessment, dry samples were milled using a Cyclotec mill through 0.5 mm sieve and analysed for N and P using wet oxidation method (McKenzie & Wallace, 1954).

2.6.4 | Maize leaf chlorophyll

Maize leaf chlorophyll measurements were recorded fortnightly on fully developed leaves. Assessments were done from V6 to R3 (milk developmental stage) using SPAD 502 Plus Chlorophyll Meter. Ten plants were randomly selected, and measurements taken on the leaf blade.

2.7 | Leaf area index (LAI) and photosynthetically active radiation assessment

The variability in leaf area index and light penetration through the crop canopy, across treatments, was conducted from V6 stage of maize development through physiological maturity of pigeonpea. The measurements were conducted within a 1 × 1 m quadrant within the net plot using AccuPAR LP-80 sensor. Six readings were staggered within the quadrant along maize rows and another eight readings taken in the intra-row spaces. Plant canopy reflectance for each treatment was calculated using Equation (1) (Koocheki et al., 2016).

$$\text{PAR fraction } (\mu\text{moLm}^{-2}\text{s}^{-1}) = (\text{AP}-\text{BP})/\text{AP}, \qquad (1)$$

where AP is the average photosynthetically active radiation above canopy and BP is the average PAR below plant canopy The leaf area index of the different cropping systems and PAR were simultaneously computed by the ceptometer during PAR assessment.

2.8 | Effect of cropping systems on crop (maize, pigeon-pea, and bean) grain quality

2.8.1 | Nutrient content in plant grain and residue biomass

After the yield of each cropping system was determined, pigeonpea leaf litter, biomass at 50% podding and grains, maize grain and stover, and bean grain and haulm samples were prepared for N and P analysis (ICRAF, 1995). Grain and vegetative biomass samples were milled using Cyclotec mill with a 0.5 mm sieve. A sample was collected to determine N and P content using wet oxidation method (McKenzie, 1954).

2.8.2 | 1000 maize grain weight

In the 2020 season, a season when Syngenta H524 and Meru H513 varieties were planted, maize was harvested, and cob samples taken to the laboratory where they were oven dried at 60°C for 24 h. Samples were shelled, grains mixed to ensure plot level homogeneity and 1000 grains randomly counted, separated, and weighed. The yields of maize, bean and pigeonpea recorded during the three seasons of the study have been published in Kinyua et al. (2023).

2.9 | Economic assessment

The independent yields for maize, beans and pigeonpea (in Kinyua et al., 2023) were converted into maize equivalent yields (MEY), allowing for an economic comparison between cereal and legume-based systems using the following equation (2).

$$\mathrm{MEY} = MY + \frac{LY \times LP}{MP \times 1000}, \tag{2}$$

where MEY = maize equivalent yield ($\mathrm{t\,ha^{-1}}$), MY = maize yield ($\mathrm{kg\,ha^{-1}}$), LY = legume yield ($\mathrm{kg\,ha^{-1}}$), LP = farm gate price of 1 kg of each of the legumes (US\$ $\mathrm{kg^{-1}}$), while MP = farm gate price of 1 kg of maize (US\$ $\mathrm{kg^{-1}}$).

The Gross income (GI; US\$ $\mathrm{ha^{-1}}$) was the cumulative revenue derived from selling the crop produce, computed using farm gate prices and before any production cost was deducted. Net revenues (NR) were the profitability of the cropping systems after production cost was deducted from the GI as indicated in the following equation (3):

$$\mathrm{NR}(\mathrm{US\$\ ha^{-1}}) = \text{Gross income(GI)} - \text{Total variable cost (TVC)}. \tag{3}$$

Total variable costs were the value of all input costs (i.e., seeds, fertiliser, agro-chemicals, and labour) incurred during crop production. To assess the return to investment for each unit of investment and fertiliser were applied, the benefit cost ratio (BCR) and value cost ratio (VCR) were calculated as indicated (Equations 4 and 5):

$$\mathrm{BCR} = (\mathrm{NR})/\mathrm{TVC}, \tag{4}$$

$$\mathrm{VCR} = (\mathrm{GI})/((\mathrm{QBF} \times \mathrm{PBF}) + (\mathrm{QTF} \times \mathrm{PTF})), \tag{5}$$

where QBF = quantity of basal fertiliser applied at sowing, PBF = price of basal fertiliser applied at sowing, QTF = quantity of fertiliser applied at top-dressing, and PTF = price of fertiliser applied at top-dressing.

2.10 | Data analysis

For the different agronomic variables assessed in multiple sampling times and seasons, that is, pigeonpea branch and flower, maize chlorophyll and the economic parameters, analysis of collected data was done using repeated measures analysis of variance. The parameters of the model included measurements from the different sampling times and/or seasons as variates, cropping systems as treatments and replicates nested within the three sites were the blocking structure run in GenStat software version 14. The repeated measures analysis of variance (ANOVA) was utilised to (also help) account for the variations introduced within the different cropping systems such as inclusion of a farmer practice in the 2020 season and planting of varying maize varieties (i.e., Meru H513, Syngenta 524 and Dekalb 8031) in different seasons to suit the prevailing weather. For aspects whose data were collected for only one time/season, that is, pigeonpea leaf abscission and 1000 maize grain weight, a one-way ANOVA was used to assess mean differences between the cropping systems. The dependent variables such as quantity of abscised leaves were used as variates, cropping systems formed the treatment structure while blocking structure was the three replicates nested within the trial sites. For the significant models, mean separation was done using least significant difference (LSD) at $p \le 0.05$.

3 | RESULTS

3.1 | Weather conditions during study

Rainfall amount and distribution varied across the study sites during the three seasons of assessment (Figure 1). The 2021 season had lowest cumulative rainfall (404 mm) though well distributed throughout the season. For the 2019 season the amount of rainfall received (542 mm) was slightly higher but poorly distributed than the 2021 season. The same (2019) had dry spells exceeding 2 weeks commencing days after seed emergence. Rainfall was well distributed in the 2020 season with amounts of up to 1565 mm. On the contrary, the 2021 season had low rainfall but high relative humidity (76.4%), though slightly lower than that of 2020 (81.2%). The 2019 season had the lowest overall relative humidity (72.6%). Minimum and maximum temperatures ranged from 6.4°C and 40.4°C in 2019, 6.7°C and 35.6°C in 2020, and 8.2°C and 30.6°C in 2021, respectively, with seasonal trends as illustrated below:

3.2 | Soil nutrient characterisation

Soils from the farmer fields and those sampled from the natural vegetation had suboptimal levels of soil organic carbon (<2.0), nitrogen (<0.2) and phosphorus (<30; Table 2). In addition, Zn (<2) and B (<0.5) were limiting in Riroda, in both the farmer practices and natural vegetation, while S (<20) was low in farmer practices of Gallapo and Riroda.

3.3 | Soil moisture

Soil moisture and temperature levels were significantly affected by site and not by treatments. Averaged across the cropping seasons, Sabilo and Gallapo villages had significantly higher soil moisture content than Riroda in at least two of the three seasons of assessment ($p \le 0.05$; Figure 2). Soil moisture ranged between 0.089 $\mathrm{m^3m^3}$ and 0.239 $\mathrm{m^3m^3}$ in the 2019 season, 0.036 $\mathrm{m^3m^3}$ and 0.162 $\mathrm{m^3m^3}$ in the 2020 season and 0.047 $\mathrm{m^3m^3}$ and 0.195 $\mathrm{m^3m^3}$ in the 2021 seasons. Soil temperatures were highest at the period between V6 and V9 and lowest between silking and physiological maturity of maize with values ranging between 24.2°C and 39.4°C, 29.4°C and 31.86°C and 25.6°C and 32.7°C in the 2019, 2020 and 2021 seasons, respectively.

3.4 | Pigeonpea branch production

The rate of pigeonpea branch production was significantly affected by the different intercropping patterns across the two seasons (2020/2021) of assessment (Table 3). Doubled-up legume system had both an early and rapid pigeonpea branch development relative to maize-based intercropping systems. When the different

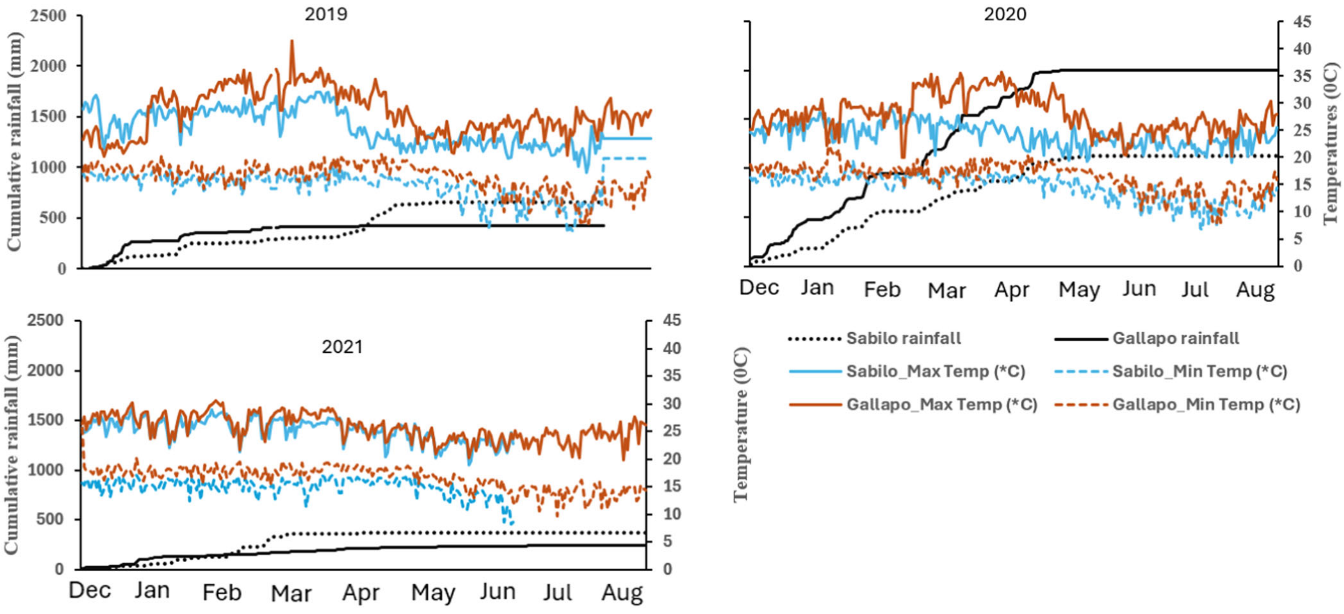

FIGURE 1 Cumulative rainfall and the maximum and minimum temperatures recorded in the study sites during the three seasons of assessment.

TABLE 2 Soil nutrient characteristics of farmer fields and undisturbed natural vegetation in Babati, Tanzania.

	Farmer practice (*n* = 6)			Natural vegetation (*n* = 3)		
Nutrient	Gallapo	Riroda	Sabilo	Gallapo	Riroda	Sabilo
pH (1:2.5 soil: H_2O)	6.7	6.5	7.0	6.8	6.5	7.1
OC (%)	2.1	0.5	1.7	1.6	1.6	3.6
N (%)	0.1	0.0	0.1	0.1	0.1	0.3
P-Olsen (ppm)	12.1	8.4	49.2	72.3	9.2	6.4
K (ppm)	795	100	1417	307	159	1573
CEC (meq/100 g)	20	6	25	23	17	51
EC (uS/cm)	46	47	96	65	94	243
Ca (ppm)	2513	760	2930	3333	2027	7623
Mg (ppm)	454	120	659	378	470	756
Mn (ppm)	304	102	365	374	160	267
S (ppm)	13	10	24	23	21	32
Cu (ppm)	6	2	13	7	3	12
B (ppm)	0.9	0.1	1.1	0.6	0.5	3.2
Zn (ppm)	4.7	0.4	1.9	16.1	1.1	2.2
Fe (ppm)	153	153	192	301	181	122
Na (ppm)	17	16	8	17	16	21

Note: Values are means for soil nutrient parameters assessed in the three study sites.

maize-pigeonpea systems were compared across the two seasons, Mbili-Mbili had relatively higher branch development than the other systems. In the period before maize harvesting, farmer practice had significantly higher branch production than the improved maize-pigeonpea system without de-topping.

3.5 | Pigeonpea flowering

The rate of flowering in pigeonpea plants was significantly affected by both the cropping system and the season of flower assessment. The difference on average flowering rate between the two seasons

FIGURE 2 Average of seasonal soil moisture content across the cropping systems ($n = 14$) in Babati, Tanzania.

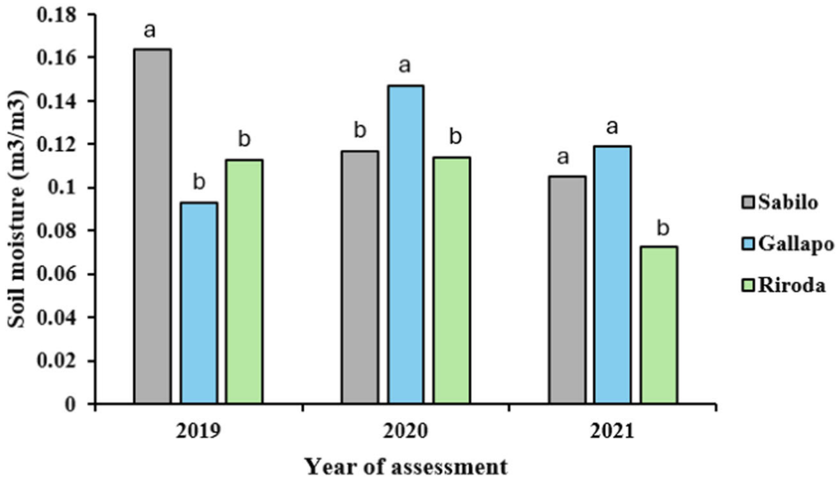

TABLE 3 Intercropping effects on pigeonpea branch production across study sites during the 2020 and 2021 cropping season in Babati, Tanzania.

Treatments	2020 2 Weeks pre-maize harvest	2021 2 Weeks post-maize harvest	4 Weeks pre-maize harvest	2 Weeks pre-maize harvest	2 Weeks post-maize harvest
Sole maize	-	-	-	-	-
Maize no de-topping	4.5c	9.6c	2.1c	5.3c	6.6d
Maize de-topped	6.4b	11.5b	2.7c	6.2bc	6.8cd
DUL	8.7a	15.9a	4.9a	8.7a	10.9a
Maize 2 plants per hill	6.0b	11.7b	2.4c	5.9bc	7.6bc
Mbili-Mbili	6.4b	11.6b	3.6b	6.9b	8.4b
Meru 513	5.6bc	11.1bc	2.6c	5.7c	7.1c
Farmer Practice€	6.2b	10.3bc	-	-	-
LSD	1.38	1.76	0.74	1.02	0.88
p-Value	0.001	0.001	0.001	0.001	0.001

Note: Means ($n = 6$) within the same column and followed by different letters are significantly different. € system only assessed in the 2020 season.

was in the range of −24% and 30% for the 2021 and 2020 season, respectively (Table 4). Doubled-up legume had the highest number of flowered pigeonpea plants across the sampling period and season ($p \le 0.01$). The rate of pigeonpea flowering in Mbili-Mbili was more stable across the two seasons relative to other maize-pigeonpea systems.

3.6 | Pigeonpea litter fall

The amount of abscised pigeonpea leaf litter was significantly affected by both the treatments ($p \le 0.01$) and sites (Figure 3; $p \le 0.05$). The quantity of leaf litter recorded across the sites was in the order of Sabilo > Riroda ≥ Gallapo with 0.8, 0.56, and 0.52 t ha^{-1} of senesced leaves, respectively. Both the DUL and farmer practice had approximately 0.5 t ha^{-1} higher leaf litter yield than the rest of the maize-pigeonpea cropping systems.

3.7 | Maize leaf chlorophyll

Except for a few cases within the sampling periods, maize leaf chlorophyll density was similar across the cropping systems and the three seasons of assessment (Supporting Information: Table S1).

3.8 | Light interception and leaf area index

The average solar radiation varied across the sites in the order of Sabilo > Riroda > Gallapo with 1595, 1418, and 1329 W m^{-2}, respectively (data not shown; $p \le 0.001$). This resulted in significant difference in solar radiation interception by crops across the sites with higher fractions in Sabilo (0.648) than Gallapo (0.538) and Riroda (0.536). The maize-pigeonpea system without de-topping had higher radiation interception than sole cropped maize for the greater part of the season (Table 5). The amount of solar radiation intercepted by

TABLE 4 Intercropping system effects on pigeon pea flowering across the study sites during the 2020 and 2021 cropping season in Babati.

	2020				2021		
Treatments	4 Weeks pre-maize harvest	2 Weeks pre-maize harvest	2 Weeks post-maize harvest	4 Weeks post-maize harvest	4 Weeks pre-maize harvest	2 Weeks pre-maize harvest	4 Weeks post-maize harvest
Sole maize	-	-	-	-	-	-	-
Maize no de-topping	0.9b	4.1b	12.9b	28.3b	3.6c	14.5d	20.27cd
Maize de-topped	1.3b	4.7b	11.2b	34.6b	6.1bc	16.6c	22.2b
DUL	8.7a	22.8a	63.9a	91.5a	22.2a	32.7a	38.3a
Maize 2 plants per hill	2.5b	7.4b	15.9b	31.7b	5.7bc	13.6d	19.8d
Mbili-Mbili	2.3b	5.9b	16.9b	30.1b	8.0b	19.9b	21.7bc
Meru 513	1.9b	6.7b	15.6b	25.67b	5.0bc	16.8c	22.67b
LSD	1.81	5.46	9.10	13.61	4.02	0.68	1.60
p-Value	0.001	0.001	0.001	0.001	0.001	0.001	0.001

Note: Means ($n = 6$) within the same column and followed by different letters are significantly different.

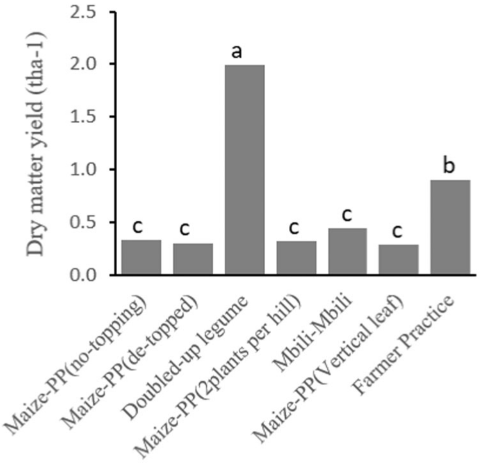

FIGURE 3 Cumulative dry matter yield from abscised pigeonpea leaves during the 2020 season in Babati.

Mbili-Mbili was significantly higher than that of other maize-pigeonpea systems from early vegetative stages (V6–V8 maize stages) until maize was harvested (i.e., 50% flowering of pigeonpea). Doubled-up legume system had consistently lower ($p \le 0.05$) radiation interception than maize-based systems during the early growth stages, however, the former had higher light interception than the latter after maize was harvested. In addition, de-topping of maize in the intercropped systems resulted in a 7% reduction in radiation interception than maize system without de-topping.

Leaf area index varied significantly across treatments and cropping seasons (Table 5; $p \le 0.001$). The differences in LAI were visible at the early stages of crop development in 2020 and not the 2019 season. Doubled-up legume had a lower leaf area index in the stages preceding pigeonpea branch and flower development as visible in the comparative trend between the 2019 and 2020 seasons. Mbili-Mbili system had consistently higher LAI relative to maize-based systems whose LAI varied across the crop growth stages. Integrating pigeonpea in the cropping systems had a positive soil cover benefit, and especially during the period after podding when the maize monocrop systems are bare following maize harvest and residue removal.

3.9 | Effect of cropping systems on 1000 maize grain weight

The two varieties of maize planted during the 2020 season had significant effects on the weight of the grain produced ($p \le 0.01$). The cropping system with Meru H513 variety had heavier maize grains than the rest which had Syngenta H524 (Figure 4).

3.10 | Effect of cropping systems on crop nutrient quality

3.10.1 | Nutrient content in maize grain

Cropping systems and sites had sigificant influence on grain and stover yield quality ($p \le 0.05$). Gallapo site had significantly lower maize grain N levels than Riroda and Sabilo villages (Supporting Information: Table S2). Contrastingly, Riroda had lower grain P and K (0.46%, 0.55%) levels than Gallapo (0.55%, 0.65%). In addition, Riroda had significantly lower (7.57 ppm) grain Mn content than Sabilo (9.54 ppm). Sole maize system had significantly lower grain N (0.84%) relative to maize-pigeonpea (No-detopping; 1.40%). Interestingly, maize toppings had higher P (2.0%) level than the lower part of stover that was retained until maize was harvested (Supporting Information: Table S3; 0.12%). Maize-pigeonpea intercrop with (0.56%) and without (0.57%) detopping had significantly higher P values than the farmer's practice (0.44%). For the stover biomass, Gallapo had

TABLE 5 Intercropping effect on light interception measured across sites during the LR 2019 and 2020 seasons in Babati Tanzania.

Treatment	Early vegetative	Late vegetative	Early reproductive	Late reproductive	Flower initiation	Half flowered	Podding
	Fraction of light intercepted in 2019 season						
Sole maize	0.224 (0.43)						
Maize no de-topping	0.190 (0.45)				0.304^{cd} (2.47^{a})		0.253^{ab} (0.74)
Maize de-topped	0.208 (0.38)				0.249^{d} (1.22^{b})		0.246^{b} (0.82)
DUL	0.179 (0.39)				0.525^{a} (2.76^{a})		0.278^{a} (0.77)
Maize 2 plants per hill	0.207 (0.43)				0.335^{bc} (2.28^{a})		0.248^{ab} (0.66)
Mbili-Mbili	0.213 (0.47)				0.378^{b} (2.49^{a})		0.23^{bc} (0.61)
Meru 513	0.141 (0.29)				0.350^{bc} (3.05^{a})		0.2084^{c} (0.69)
LSD	0.060				0.070 (1.03)		0.030 (0.28)
p-Value	0.078				0.001 (0.02)		0.001 (0.72)
	Fraction of light intercepted in 2020 Season						
Sole maize	0.288^{b} (0.92^{ab})	0.714^{b} (3.04^{bc})	0.846^{bc} (4.14^{ab})	0.711^{ab}	0.685^{d}	0.722^{bcd}	
Maize no de-topping	0.336^{a} (0.95^{ab})	0.710^{b} (2.93^{bc})	0.886^{a} (4.34^{a})	0.701^{ab}	0.724^{bc}	0.744^{ab}	0.299^{b}
Maize de-topped	0.284^{b} (0.84^{b})	0.768^{a} (3.12^{ab})	0.864^{b} (4.24^{a})	0.649^{c}	0.698^{cd}	0.676^{e}	0.226^{cd}
DUL	0.131^{d} (0.42^{d})	0.290^{d} (0.82^{e})	0.395^{e} (1.09^{c})	0.386^{d}	0.533^{f}	0.737^{bc}	0.485^{a}
Maize 2 plants per hill	0.244^{c} (0.63^{c})	0.713^{b} (2.74^{c})	0.819^{d} (3.85^{b})	0.675^{bc}	0.619^{e}	0.694^{de}	0.270^{bc}
Mbili-Mbili	0.347^{a} (1.09^{a})	0.783^{a} (3.40^{a})	0.836^{cd} (4.12^{ab})	0.730^{a}	0.774^{a}	0.784^{a}	0.208^{d}
Meru 513	0.296^{b} (0.84^{b})	0.667^{c} (2.37^{d})	0.834^{cd} (4.40^{a})	0.681^{bc}	0.746^{ab}	0.695^{cde}	0.289^{b}
LSD	0.032 (0.13)	0.032 (0.22)	0.021 (0.24)	0.041	0.038	0.043	0.045
p-Value	0.001 (0.001)	0.001 (0.001)	0.001 (0.001)	0.001	0.001	0.001	0.001

Note: Early vegetative = maize between V6 and V8; late vegetative = maize around V11; early reproductive = maize around R1; late productive = maize around R4 stages of growth; flower initiation = pigeonpea at early flowering; half flowered = pigeonpea at 50% flowering and podding = 50% podding. Data on fraction of radiation inception between late vegetative and late reproductive stages of maize in 2019 is missing due to technical hitch that affected the AccuPAR LP-80 device. Means ($n = 6$) indicated in parentheses represent the LAI for each of the cropping system; recorded until the early reproductive stage of pigeonpea in 2020 season.

FIGURE 4 Effect of cropping system on the average 1000 maize grain weight across sites ($n = 6$) during the 2020 season. Maize variety planted during this season was Syngenta H524, except in the system where Meru 513 has been specified.

significantly higher P both in the maize toppings (0.26%) than those havested from Sabilo (0.14%). In addition, three of improved cropping systems namely sole maize (2.11%), Mbili-Mbili (6.03%) and maize-pigeonpea (1.9%) without detopping had significantly higher maize stover K levels than the farmer practice.

3.10.2 | Nutrient content in pigeonpea biomass

The accumulation of nutrients in abscised pigeonpea leaves was significantly different across the site and not the cropping systems. The concentration of N and K in pigeonpea litter was higher in Sabilo (2.4% and 1.1%, respectively) than Gallapo (2.0% and 0.8%, respectively) and Riroda (1.8% and 0.6%, respectively). Nutrient concentration in pigeonpea above ground biomass, at 50% podding, was significantly affected by both the sites and the cropping systems. Sabilo had higher N, P and K in pigeonpea biomass, that is, 2.14%, 0.30% and 1.57% than Gallapo, that is, 1.81%, 0.25% and 1.06, respectively. Averaged across the sites, contrast analysis between improved maize-pigeonpea (no-detopping) and the farmer practice showed the former having significantly higher Ca, Fe and Cu accumulation than the latter ($p \leq 0.05$; Table 6).

3.10.3 | Bean grain and haulms

The N content in bean grain was higher in Mbili-Mbili (2.8%) than DUL (Table 7; 1.8%). A similar trend was visible in the haulms where N levels were higher in Mbili-Mbili system (1.4%) than DUL (0.7%). Conversely, haulms of the latter had double the amount of K (1.4%) recorded in the former (0.7%).

TABLE 6 Nutrient concentration of pigeonpea biomass at 50% podding during the 2020 season in Babati, Tanzania.

Cropping systems (*n* = 6)	Maize-pigeonpea (no-detopping)	Farmer practice	Significance
N (%)	2.2	1.8	
K (%)	1.4	1.1	
P (%)	0.3	0.3	
S (%)	0.2	0.1	
Zn (ppm)	27	20	
Cu (ppm)	14	9	*
B (ppm)	32	24	
Ca (%)	0.9	0.7	*
Fe (ppm)	1306	781	**
Mo (ppm)	1.8	2.9	
Mn (ppm)	105	73	
Mg (%)	0.2	0.2	

***Shows significance at $p \leq 0.001$ probability level, **significant at $p \leq 0.01$ probability level, *significant at $p \leq 0.05$ probability level.

TABLE 7 Bean grain and haulm nutrient content across the two cropping systems.

Cropping system	N (%)	P (%)	K (%)
	Bean grain		
Mbili Mbili	2.76	0.48	1.5
Doubled-up legume	1.75	0.46	1.48
	Bean haulms		
Mbili Mbili	1.39	0.15	0.75
Doubled-up legume	0.75	0.21	1.39

Note: Values are means ($n = 6$) of bean grain and haulm nutrient content across the two cropping systems.

3.11 | Maize equivalent yields, benefit cost ratio and value cost ratio

The maize equivalent yields, net revenue, benefit to cost ratio and value to cost ratio were significantly affected by both the cropping systems and seasons ($p \leq 0.05$). On average, the 2020 and 2021 seasons had significantly higher maize equivalent yields, that is, 6.1 t ha^{-1} and 8.2 t ha^{-1}, respectively, than the 2019 (1.9 t ha^{-1}) season ($p \leq 0.05$; Table 8). Doubled-up legume had consistently lower maize equivalent yields than the maize-based systems, except for the 2021 season where it superseded that of the latter ($p \leq 0.001$). Mbili-Mbili system also had consistently higher maize equivalent yields than other maize-based systems, across the cropping seasons. This made Mbili-Mbili attain consistently higher net revenues across the study period. On the contrary, DUL had inconsistent net revenues after it attained the lowest revenues in 2019 but had the highest in the 2021 season. The initial cost of establishing (planting) Mbili-Mbili was 21% and 55% higher, despite the system being 49% and 57% cheaper to weed when compared to Maize-pigeonpea (no de-topping) and DUL, respectively (data not shown). While all treatments had a BCR < 1 in 2019 and BCR > 1 in the 2020 season, only DUL, Mbili-Mbili and farmer practice attained a profitable benefit to cost ratio (BCR ≥ 1) in the 2021 season. All cropping systems had a VCR that was >2 throughout the study period. However, in the 2021 season, Mbili-Mbili system had a VCR of 8.1 which was not only significantly higher than other cropping systems but also the highest across the study period.

4 | DISCUSSION

This study unveils the benefits and deleterious effects of cereal-based systems on the phenological traits of the intercropped legume and cereal crops, and the opportunity offered by exploring different plant spatial configurations. Seasonal weather variations also had a great bearing on the physiological development and attainable yields of rainfed systems, predominant in smallholder farms of SSA. The study area has undulating terrain which might have contributed to the sharp rainfall, temperature, and soil fertility gradients. Similar

TABLE 8 Maize equivalent yields (MEY; t ha^{-1}), annual net benefits (NP; US$), benefit-to-cost ratio (BCR) and value-to-cost ratio (VCR) across sites implemented in Babati, Northern Tanzania between the 2019 and 2021 cropping seasons.

Treatment	MEY	NP 2019	BCR	VCR	MEY	NP 2020	BCR	VCR	MEY	NP 2021	BCR	VCR
Sole maize	2.0^{a}	37^{c}	0.7^{ab}	3.7^{a}	6.2^{a}	$1,112^{a}$	1.7^{abc}	5.5^{a}	5.5^{c}	269^{d}	0.4^{d}	4.4^{c}
Maize no de-topping	2.0^{a}	291^{abc}	0.5^{abc}	3.8^{a}	5.9^{a}	994^{a}	1.4^{bc}	5.3^{a}	6.5^{bc}	368^{cd}	0.5^{cd}	5.2^{bc}
Maize de-topped	1.9^{ab}	207^{abc}	0.4^{bcd}	3.5^{a}	6.5^{a}	$1,156^{a}$	1.4^{bc}	5.5^{a}	7.3^{bc}	499^{cd}	0.7^{cd}	5.9^{b}
Doubled-up legume	1.2^{b}	343^{ab}	0.1^{d}	-	4.3^{b}	992^{a}	2.0^{a}	-	12.2^{a}	1438^{a}	2.5^{a}	-
Maize 2 plants per hill	1.7^{ab}	141^{bc}	0.2^{cd}	3.1^{a}	6.1^{a}	970^{a}	1.3^{bc}	5.2^{a}	7.9^{b}	578^{c}	0.8^{c}	6.3^{b}
Mbili-Mbili	2.4^{a}	418^{a}	0.8^{a}	4.2^{a}	6.7^{a}	$1,200^{a}$	1.7^{ab}	5.9^{a}	10.3^{a}	987^{b}	1.3^{b}	8.1^{a}
Meru 513	2.1^{a}	320^{ab}	0.6^{abc}	3.9^{a}	6.7^{a}	$1,108^{a}$	1.5^{abc}	5.7^{a}	7.5^{b}	520^{cd}	0.7^{cd}	5.9^{b}
Farmer practice$^{€}$	-	-	-	-	3.0^{c}	413^{b}	1.3^{c}	-	6.0^{bc}	524^{cd}	1.2^{b}	-
p-Value	0.05	0.05	0.008	0.372	0.001	0.003	0.047	0.513	0.001	0.001	0.001	0.001
LSD	0.74	273.5	0.38	0.99	1.25	434.2	0.44	0.72	2.02	301.0	0.34	0.82

Note: Means (*n* = 6) within the same column and followed by different letters are significantly different.

$^{€}$Treatment assessed only in the 2020 and 2021 cropping season.

seasonal weather variability resulting from the heterogeneity in topographical alignment were reported by Mugi-Ngenga et al. (2023), with dry spells of between 40 and 70 days that coincided with early stages of crop development. These factors are likely to have influenced the crop phenological growth resulting in variation in crop physiological parameters across the period of study. Moreover, some areas like Riroda are sandy (67.3% sand) with low proportions of clay (12%) which might have also significantly affected crop productivity (Msigwa, 2018; Mugi-Ngenga et al., 2022a), especially during poor rainfall seasons like 2019. This informs the need for investing in climate information services for timely and accurate seasonal weather predictions (Antwi-Agyei et al., 2021) to guide on field operations, including choice of suitable cropping systems and intercrop components to improve farmer resilience to changing climate.

Nutrient deficiency in the different sites was an indication that soils of the study area have inherently low nutrient levels. The low levels of carbon in cultivated fields relative to that of natural vegetation can be attributed to continuous disturbance of soil through tillage. The low adoption of soil and water conservation strategies and organic resource flows from crop fields to homefields by 76% of households, for livestock fodder, (Mponela et al., 2022) also contributes to reduced soil organic carbon. The Ferritic nature of the soil might have enhanced fixing of soil P resulting in its deficiency. Soil in Riroda had limited Zn (<2.0) and B (<0.5) which can be attributed to its sandy nature, that could have reduced its nutrient holding capacity. Integration of inorganic fertilisers (mainly N and P) and manure coupled with good agronomic practices is a potential strategy for unlocking crop yields in the area. For Riroda, use of Zn and B blended fertilisers or applying micronutrients in foliar form can help to overcome the associated deficiencies in growing crops.

The intercropping of pigeonpea and beans under DUL offered spatial temporal complementarity of resource capture (Wu et al., 2012) allowing beans to develop and mature early in the season without affecting growth and development of the slow growing pigeonpea. This resulted in the early and rapid branch development in pigeonpea compared to that of maize-based system where interspecific competition for light, moisture and nutrients might have led to the late and slow branching of intercropped pigeonpea. The spacing and complementarity of the growth pattern of three crops species under Mbili-Mbili provided room for an earlier pigeonpea branch development than the other maize-pigeonpea systems Adopting intercropping systems that allow for enhanced branch development such as DUL and Mbili-Mbili can form an important source of firewood (Smith et al., 2016) while the associated leaf biomass can be used as a rich mulch cover and supplementary livestock feed during the fodder scarce dry seasons. This agrees with findings by Neugschwandtner and Kaul (2014) on the significance of plant row ratio in influencing intercropping efficacy. The greater number of branches in the farmer practice than the improved maize-pigeonpea system was unusual. The less than 15% adoption of fertiliser use by farmers in Babati (Adu-Gyamfi et al., 2007; Kihara et al., 2015) can be linked to low performance of maize in farmer practices resulting in reduced competition for growth resources on the intercropped pigeonpea. In addition, farmers in the area broadcast seeds behind tractors or animal drawn ploughs. This practice results in deep burying of seeds, hence a poor cereal and legume crop establishment which benefits the development of pigeonpea.

The weather conditions within the season had a significant bearing on the rate of flower development in pigeonpea. The 2020 season had 1160 mm higher rainfall than the 2021 season which might have been unfavourable for pigeonpea flower development. Pigeonpea crop is drought tolerant and performs well in warm weather. In addition, high rainfall within the season might have triggered flower abscission in the pigeonpea crop. Indeed, an average pigeonpea yield of 0.65 t ha^{-1} was attained in 2020 relative to 1.2 t ha^{-1} in 2021 in the same sites (Kinyua et al., 2023). The high rate of flower development in DUL and Mbili-Mbili is also consistent with the higher branch development in the two systems and attributed to improved access to solar radiation.

Intercropping systems comprising only pigeonpea and beans have reduced competition for growth resources, thus enhancing the proliferation of both legumes. This is because the two crops have varying rates of growth, levels of nutrient and water extraction and forms canopies at different periods (Mugi-Ngenga et al., 2022b). This gives DUL a production advantage that enhances the development and shedding of higher amounts of pigeonpea leaf litter than in maize-based systems. A similar case can be seen in farmer practices where pigeonpea outgrows maize because of the low soil fertility levels. The 2 m-long pigeonpea root system gives it a competitive advantage over the shallow rooted maize, as it can break through the soil hardpan, access leached nutrients and infiltrated water from deep soil layers. Moreover, soils with low mineral N favours effective legume–rhizobia symbiosis (Peoples et al., 2009) promoting biological fixation of N thus producing a high dry matter yield than in the improved maize-pigeonpea systems where inorganic fertilisers bolsters maize growth. Abscissions of between 1 and 2 t ha^{-1} of leaf litter from farmer practice and DUL can help in replenishing nutrients in the topsoil while enhancing moisture conservation (Rapholo et al., 2020). This not only improves the yields of the subsequent cereal crop, by generating upto 95 kg N ha^{-1} (Sakala, 1998), but also helps to promote soil health. Mugi-Ngenga et al. (2022b) indicated pigeonpea litter biomass as the primary contributor to increased yields of the subsequent maize crop. Contrastingly, Mwila et al. (2021) reported that this relationship may not be visible under short-term conservation agriculture systems. Interestingly, Ncube et al. (2007) reported fallen leaves as more important than retaining the legume residues after harvest. For Babati and other regions characterised by low fertiliser adoption and residue removal after crop harvest (Kihara et al., 2015), pigeonpea litter can significantly reduce investment on the expensive and inaccessible inorganic fertilisers. However, proper nutrient management strategies need to be put in place to avoid volatilisation of N during the long dry season, between harvesting and commencement of subsequent season.

The chlorophyll content in plant leaves using SPAD measurements has been widely used as a proxy of N concentration, hence a good measure of N deficiency in a crop. Lack of significant difference in maize SPAD leaf measurements across the cropping systems was an important indicator of the efficiency that the spatial configuration of Mbili-Mbili offers through increased crop diversification with no penalty on N uptake by maize plants. Zhang and Li (2003) emphasised the need for technologies characterised by reasonable use of competitive and facilitative interactions under intercropping systems to enhance crop productivity and nutrient use efficiency. Any promising innovation resulting in maize yield reduction is likely to face resistance to adoption by smallholder farmers. This is because maize plays a significant role both as a staple crop and in income generation, attributes that farmers would not be ready to compromise for increased legume yields.

The sharp landscape gradient shaping the elevation, aspect and agroecological positioning of the three sites might have contributed to the variation in light interception across the trial sites. The differences in radiation interception are also consistent with variation in crop yields reported across the sites, with Sabilo having significantly higher maize and pigeonpea yields than Gallapo and Riroda (Kinyua et al., 2023). These findings are consistent with Kihara et al. (2015) who described the study area as having undulating terrain that strongly influences its temperatures, rainfall, and resulting in a soil fertility gradient. The higher radiation interception in maize–pigeonpea intercropping than the sole maize system is an indication that intercropping systems are effective utilizers of PAR than the monocrop systems. The influence of cropping systems on soil health was also evident in the period after maize harvest. Maize-pigeonpea systems had a legume cover that lasted for 4 months, in addition to upto 2 t ha^{-1} of abscised litter mulch beyond pigeonpea harvest, while soil under the sole maize remained bare for the whole period. Mbili-Mbili showed a high radiation interception throughout the season (except at pigeonpea podding stage) which is consistent with higher branch and flower development than other maize-based intercropping systems. The multiple crop species within Mbili-Mbili provided some level of canopy cover at variable times of the season, starting with beans, maize and later pigeonpea. The presence of a crop cover in the greater part of the season is an indication of Mbili-Mbili offering optimal radiation use efficiency relative to other cropping systems that had delayed canopy development. Zhang et al. (2015) reported high light use efficiency in the two border maize rows when four maize rows were alternated with six soybean rows, depicting the efficacy of Mbili-Mbili with double maize rows during this study. This efficacy in light use efficiency makes Mbili-Mbili a suitable option for weed suppression, temperature moderation (Borowy, 2012; Katsaruware & Manyanhaire, 2009), enhanced crop water productivity and soil conservation (Chimonyo et al., 2016; Sharaiha & Hadidi, 2007). Unlike Mbili-Mbili, DUL had low radiation interception and LAI in the period preceding pigeonpea podding that can be attributed to slow rate of pigeonpea growth and the low canopy cover created by the bush bean variety. In seasons characterised by poor rainfall distribution, that is, the 2019 with 540 mm, systems with low LAI such as DUL are susceptible to increased evapotranspiration and moisture stress, potentially causing economic losses of upto 26% (Kinyua et al., 2023; Mwila et al., 2021).

At its early stage of establishment, DUL (consisting of beans and pigeonpea) could be prone to weed invasion (Mashingaidze, 2004) increasing drudgery, and exposing soil to degradation through runoff associated erosion. However, the advantage of DUL by having a reduced canopy cover is visible during the productive stages of pigeonpea as evident by an earlier branch and flower development, higher radiation interception at podding and upto 35% more pigeonpea grain yield than in maize-based systems (Kinyua et al.,2023). De-topping maize at physiological maturity can be explored as a potential strategy for increasing light penetration to legumes. This was evident by increased pigeonpea branch and flower development, a finding consistent with the relationship established by Kinyua et al. (2023) on de-topping increasing pigeonpea grain by 15.4% and haulm yield by 94.3%.

Crop variety had an important contribution to the weight of the maize grain as was evident by higher grain weight in Meru H513 relative to Syngenta H524 variety. Meru H513 is a drought tolerant variety and might also possess an inherent genotypical trait that enhances grain weight gain relative to Syngenta H524 variety. The differences in grain weight between the two varieties agrees with the 17.4% loss in maize yield following crop exposure to heat related stress during the reproductive stages (Huan et al., 2020; Tesfaye et al., 2017; Zhao et al., 2017). Temperature range of between 29.2°C and 33.6°C was recorded during the maize reproductive stage, which might have favoured mass accumulation in the drought tolerant Meru H513 against the Syngenta variety.

A relationship between the amount of nutrients in the soil and amounts accumulated in the grain was established. For example, the sandy soils in Riroda had critically low P of 8.4 ppm relative to 12 ppm in Gallapo, a condition reflected in maize grain P allocation in the two sites. Similar trend of soil–grain nutrient relationship was observed for NPK and micronutrients in maize and pigeonpea across sites, an indicator that embracing integrated soil fertility management (ISFM), good agronomic practices and soil and water conservation could enhance soil quality. Higher NPK in pigeonpea in Sabilo than Gallapo can also be attributed to dilution effect. Similar N dilution effect was observed in maize grain of the sole maize system which had an average of 0.8 t ha^{-1} more grain than maize–pigeonpea with no-detopping (see Kinyua et al., 2023). For beans under Mbili-Mbili during this study, yields were 2–6 times lesser than that of DUL (ibid). Zhang et al. (2015) attributed the higher N levels in intercrops than the sole crops to the higher amount of combined grain and biomass in intercrops while Baldé et al. (2011) associated it with efficient uptake of N in the intercropped systems. Application of Minjingu Nafaka Plus also had a significant influence on the allocation of P in maize grain of improved systems relative to the unfertilised farmer practice. The soils of the study area are dominantly Ferralsols (Adu-Gyamfi et al., 2007), characterised by high P fixation, which might have reduced the produce quality under farmer practice. Fertiliser application in farmer practices would not only improve produce qulity but also compensate for the nutrient mined through residue removal and communal grazing in crop fields. The higher P content in maize toppings than the lower part of stover can be attributed to higher nutrient allocation in the upper than lower plant biomass. Feeding livestock with maize toppings could provide livestock with higher levels of P, while the lower part can be incorporated in the soil to enhance soil carbon content.

Soil texture had a significant influence on the ability to retain moisture for use by the growing crop. Soils in Riroda have sand content of upto 80.3% that might have contributed to the lower soil moisture retention capacity relative to those in Sabilo and Gallapo. In seasons characterised by poor rainfall amounts such as the 2021 season, soils in Riroda could easily loose moisture resulting in moisture stress and yield reduction. Taking advantage of cropping system innovations such as Mbili-Mbili or DUL, with a rapid—establishing legume covercrop (Chimoyo et al., 2016), and suplementing it with manure and residue mulch would offer a good soil cover for preserving soil moisture.

A unit of investment in fertiliser within the study area was observed to be economically viable considering all systems attained a VCR > 2, a profitable threshold for use of fertilisers (Kihara et al., 2015). Utilising N and P fertilisers was a profitable investment since the two nutrients were deficient across the study area. Indeed, Kihara et al. (2020) indicated that a judicious application of 50 kg N ha^{-1} and 20 kg P ha^{-1} is profitable and sustainable for maize-based systems of Babati. The high return on investment under Mbili-Mbili than other cereal-based systems is an indicator that its profitability is strongly embedded on richness in crop diversity and complemented by application of inorganic fertiliser. Indeed, different studies have emphasised on need for integrating ISFM practices such as inorganic fertilisers (Kinyua et al., 2021; Vanlauwe et al., 2011) and adopting crop diversification (Snapp & Fisher, 2015) to enhance sustainable production and increase farmer resilience to climate change. The two seasons (2020 and 2021) where Mbili-Mbili had BCR > 1 compared to the rest of improved cereal-legume systems (in 2021) and its consistently higher maize equivalent yields also indicates an enhanced yield stability across variable seasonal weather. While DUL (involving pigeonpea and beans) could be a promising system with net revenues of up to US$ 1400 ha^{-1}, the system is vulnerable to variable weather. For this reason, its implementation by farmers should be guided by seasonal weather forecasts to avoid yield loss. Despite being a promising innovation, Mbili-Mbili system was both labour and cost intensive thus would require farmers to prepare adequate resources during planting. However, the dense canopy created by the intercropped components suppressed weeds resulting in lower weeding cost than all other improved practices, thus allowing farmers to regain some resources invested during planting (Kinyua et al., 2023).

5 | CONCLUSION

Exploring the plant spatial configurations for enhanced legume growth seems to be a promising strategy for optimising the productivity of intercropping systems. Doubled-up legume system comprising pigeonpea and beans was efficient in promoting pigeonpea branch and flower development and producing upto 2 t ha^{-1} of mulch cover. However, the low radiation use efficiency in DUL would expose the system to erosion and direct sunlight during the early crop establishment stages or poor seasons. On the other hand, Mbili-Mbili performed better than other maize-based systems in this study as the spatial arrangement of the intercropped species enhanced a spatial temporal complementarity overcoming competition for growth resources. The system has a good radiation use efficiency which could help to improve legume yields and cover the soil from agents of erosion. Maize–pigeonpea systems were more efficient in enhancing soil health than the sole maize system. Moreover, simple management practices like detopping could help improve intercropping benefits while toppings can be used as P-rich livestock fodder.

The findings of this study underscore the importance of adopting intercropping/rotations with appropriate spatial configuration strategies, within ISFM frameworks, to optimise productivity and sustainability in smallholder farming systems. By embracing crop diversification strategies like Mbili Mbili, farmers can increase their systems' resilience to seasonal weather variability while simulteneously increasing soil health benefits such as reduced erosion and improved soil cover. In addition, farmers in SSA can improve crop production amidst the challenge of reducing arable farmlands. Moreover, it highlights the need for integrating climate information services in smallholder systems to enable farmers to benefit from promising innovations like DUL (involving pigeonpea and beans), which have high marginal returns but are susceptible to seasonal weather variability.

AUTHOR CONTRIBUTIONS

Michael W. Kinyua: Conceptualisation; design, fieldwork; data collection; laboratory work; data cleaning and analysis; statistical analysis; visualisation; investigation; writing—original draft; writing—review and editing. **Monicah W. Mucheru-Muna**: Supervision; writing—review and editing. **Peter Bolo**: Writing—review and editing. **Job Kihara**: Conceptualisation; funding acquisition; investigation; supervision; review.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions. Data will be made available on request.

ETHICS STATEMENT

The authors confirm that they have adhered to the ethical policies of the journal.

REFERENCES

Adu-Gyamfi JJ, Myaka FA, Sakala WD, Odgaard R, Vesterager JM, Høgh-Jensen H. Biological nitrogen fixation and nitrogen and phosphorus budgets in farmer-managed intercrops of maize–pigeonpea in semi-arid Southern and Eastern Africa. Plant Soil. 2007;295(1):127–36.

Antwi-Agyei P, Amanor K, Hogarh JN, Dougill AJ. Predictors of access to and willingness to pay for climate information services in north-eastern Ghana: a gendered perspective. Environ Dev. 2021;37:100580.

Baldé AB, Scopel E, Affholder F, Corbeels M, Da Silva FAM, Xavier JHV, et al. Agronomic performance of no-tillage relay intercropping with maize under smallholder conditions in central Brazil. Field Crops Res. 2011;124(2):240–51.

Borowy A. Growth and yield of stake tomato under no-tillage cultivation using hairy vetch as a living mulch. Acta Scientiarum Polonorum. Acta Sci Pol Hort Cult. 2012;11(2):229–52.

Caviglia OP, Sadras VO, Andrade FH. Yield and quality of wheat and soybean in sole-and double-cropping. Agron J. 2011;103(4):1081–9.

Chikowo R, Chimonyo V, Gwenambira C, Snapp S. Ecosystem services in doubled-up legume systems. The role of ecosystem services in sustainable food systems. Cambridge: Academic Press; 2020. p. 171–80.

Chimonyo VGP, Modi AT, Mabhaudhi T. Water use and productivity of a sorghum cowpea-bottle gourd intercrop system. Agricult Water Manag. 2016;165:82–96.

International Centre for Research in Agroforestry (ICRAF) (1995). Laboratory methods for soil and plant analysis, Version 1.1, Nairobi.

Katsaruware RD, Manyanhaire IO. Maize-cowpea intercropping and weed suppression in leaf stripped and detasselled maize in Zimbabwe. Electron J Environ Agric Food Chem. 2009;8(11):1218–26.

Kermah M, Franke AC, Adjei-Nsiah S, Ahiabor B, Abaidoo RC, Giller KE. N2-fixation and N contribution by grain legumes under different soil fertility status and cropping systems in the Guinea savanna of Northern Ghana. Agric Ecosyst Environ. 2018;261:201–10.

Kihara J, Kizito F, Jumbo M, Kinyua M, Bekunda M. Unlocking maize crop productivity through improved management practices in Northern Tanzania. Afr J Food Agric Nutr Dev. 2020;20(7):17095–112.

Kihara J, Tamene LD, Massawe P, Bekunda M. Agronomic survey to assess crop yield, controlling factors and management implications: a case-study of Babati in Northern Tanzania. Nutr Cyc Agroecosyst. 2015;102:5–16.

Kimaro AA, Timmer VR, Chamshama SAO, Ngaga YN, Kimaro DA. Competition between maize and pigeon-pea in semi-arid Tanzania: effect on yields and nutrition of crops. Agric Ecosyst Environ. 2009;134:115–25.

Kinyua MW, Kihara J, Bekunda M, Bolo P, Mairura FS, Fischer G, et al. Agronomic and economic performance of legume-legume and cereal-legume intercropping systems in Northern Tanzania. Agricult Sys. 2023;205:103589.

Koocheki A, Mahallati MN, Solouki H, Karbor S. Evaluation of radiation absorption and use efficiency in substitution intercropping of sesame (*Sesamum indicum L.*) and mung bean (*Vigna radiata L.*). Adv Plants Agric Res. 2016;3(5):01–9.

Li QZ, Sun JH, Wei XJ, Christie P, Zhang FS, Li L. Overyielding and interspecific interactions mediated by nitrogen fertilization in strip intercropping of maize with faba bean, wheat and barley. Plant Soil. 2011;339:147–61.

Mashingaidze AB. Improving weed management and crop productivity in maize systems in Zimbabwe. Wageningen: PhD thesis. Wageningen University; 2004.

Mashingaidze AB, Katsaruware RD. Upright varieties out-yield climbing cowpea varieties and leaf stripping and detasselling enhances productivity of maize/cowpea intercrops. Nairobi: JKUAT Annual Scientific Conference Proceedings; 2010. p. 761–9.

McKenzie H, Wallace H. The Kjeldahl determination of nitrogen: a critical study of digestion conditions-temperature, catalyst, and oxidizing agent. Aust J Chem. 1954;7(1):55–70.

Mehlich A. Mehlich 3 soil test extractant: a modification of Mehlich 2 extractant. Commun Soil Sci Plant Anal. 1984;15(12):1409–16.

Minot N. Staple food prices in Tanzania. Variation in staple food prices: causes, consequence, and policy options. Maputo, Mozambique: African Agricultural Marketing Project (AAMP); 2010. p. 25–6.

Mponela P, Manda J, Kinyua M, Kihara J. Participatory action research, social networks, and gender influence soil fertility management in Tanzania. Syst Pract Action Res. 2022;36(1):1–23.

Msigwa ZP. Adaptation to rainfall variability, socioeconomic factors influencing maize production in crop livestock mixed farming systems in Babati district, Tanzania (Doctoral dissertation)Tanzania: Sokoine University of Agriculture; 2018. p. 101.

Mucheru-Muna M, Pypers P, Mugendi D, Kung'u J, Mugwe J, Merckx R, et al. A staggered maize–legume intercrop arrangement robustly increases crop yields and economic returns in the highlands of Central Kenya. Field Crops Res. 2010;115(2):132–9.

Mugi-Ngenga E, Bastiaans L, Anten NPR, Zingore S, Baijukya F, Giller KE. The role of inter-specific competition for water in maize-legume intercropping systems in Northern Tanzania. Agricult Sys. 2023;207:103619.

Mugi-Ngenga E, Bastiaans L, Anten NPR, Zingore S, Giller KE. Immediate and residual-effects of sole and intercropped grain legumes in maize production systems under rain-fed conditions of Northern Tanzania. Field Crops Res. 2022a;287:108656.

Mugi-Ngenga E, Bastiaans L, Zingore S, Anten NPR, Giller KE. The role of nitrogen fixation and crop N dynamics on performance and legacy effects of maize-grain legumes intercrops on smallholder farms in Tanzania. Eur J Agron. 2022b;141:126617.

Mugi-Ngenga E, Zingore S, Bastiaans L, Anten NPR, Giller KE. Farm-scale assessment of maize–pigeonpea productivity in Northern Tanzania. Nutr Cyc Agroecosyst. 2021;120(2):177–91.

Mwila M, Mhlanga B, Thierfelder C. Intensifying cropping systems through doubled-up legumes in Eastern Zambia. Sci Rep. 2021;11(1):8101.

Ncube B, Twomlow SJ, Van Wijk MT, Dimes JP, Giller KE. Productivity and residual benefits of grain legumes to sorghum under semi-arid conditions in southwestern Zimbabwe. Plant Soil. 2007;299:1–15.

Neugschwandtner RW, Kaul HP. Sowing ratio and N fertilization affect yield and yield components of oat and pea in intercrops. Field Crops Res. 2014;155:159–63.

O'Leary N, Smith ME. Uncovering corn adaptation to intercrop with bean by selecting for system yield in the intercrop environment. J Sustain Agric. 2004;24(3):109–21.

Peoples MB, Brockwell J, Herridge DF, Rochester IJ, Alves BJR, Urquiaga S, et al. The contributions of nitrogen-fixing crop legumes to the productivity of agricultural systems. Symbiosis. 2009;48:1–17.

Prasad RB, Brook RM. Effect of varying maize densities on intercropped maize and soybean in Nepal. Exp Agric. 2005;41(3):365–82.

Rapholo E, Odhiambo JJO, Nelson WCD, Rötter RP, Ayisi K, Koch M, et al. Maize–lablab intercropping is promising in supporting the sustainable intensification of smallholder cropping systems under high climate risk in Southern Africa. Exp Agric. 2020;56(1):104–17.

Rusinamhodzi L, Corbeels M, Nyamangara J, Giller KE. Maize–grain legume intercropping is an attractive option for ecological intensification that reduces climatic risk for smallholder farmers in central Mozambique. Field Crops Res. 2012;136:12–22.

Sakala W. Nitrogen dynamics in maize *(Zea mays)* and pigeonpea *(Cajanus Cajan)* intercropping in Malawi. Ashford: Wye College, University of London; 1998.

Sharaiha RK, Hadidi NA. Environmental impact on yield of peas and okra grown under intercropping. Lucrâri stiittifice. 50. Iași, Romania: Universitatea de Ştiinţe Agricole şi Medicină Veterinară Iaşi; 2007. p. 313–23.

Smith A, Snapp S, Dimes J, Gwenambira C, Chikowo R. Doubled-up legume rotations improve soil fertility and maintain productivity under variable conditions in maize-based cropping systems in Malawi. Agricult Sys. 2016;145:139–49.

Snapp SS, Fisher M. "Filling the maize basket" supports crop diversity and quality of household diet in Malawi. Food Security. 2015;7:83–96.

Tesfaye K, Zaidi PH, Gbegbelegbe S, Boeber C, Rahut DB, Getaneh F, et al. Climate change impacts and potential benefits of heat-tolerant maize in South Asia. Theor Appl Climatol. 2017;130(3):959–70.

Vagen T, Shepherd KD, Walsh MG, Winowiecki L, Desta LT, Tondoh JE. Afsis technical specifications: soil health surveillance. Africa Soil Information Service (AfSIS). Nairobi, Kenya: World Agroforestry Centre; 2010.

Vanlauwe B, Kihara J, Chivenge P, Pypers P, Coe R, Six J. Agronomic use efficiency of N fertilizer in maize-based systems in sub-Saharan Africa within the context of integrated soil fertility management. Plant Soil. 2011;339:35–50.

Woomer PL, Lan'gat M, Tungani JO. Innovative maize-legume intercropping results in above-and below-ground competitive advantages for understorey legumes. West Afr J Appl Ecol. 2004;6(1):45609.

Wu K, Fullen MA, An T, Fan Z, Zhou F, Xue G, et al. Above-and below-ground interspecific interaction in intercropped maize and potato: a field study using the 'target' technique. Field Crops Res. 2012;139: 63–70.

Zhang F, Li L. Using competitive and facilitative interactions in intercropping systems enhances crop productivity and nutrient-use efficiency. Plant Soil. 2003;248:305–12.

Zhang Y, Liu J, Zhang J, Liu H, Liu S, Zhai L, et al. Row ratios of intercropping maize and soybean can affect agronomic efficiency of the system and subsequent wheat. PLoS One. 2015;10(6):e0129245.

Zhao C, Liu B, Piao S, Wang X, Lobell DB, Huang Y, et al. Temperature increase reduces global yields of major crops in four independent estimates. Proc Natl Acad Sci USA. 2017;114(35):9326–31.

SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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